Solar Energy Vol. 39, No. 4, pp. 361–367, 1987
Printed in the U.S.A.

0038-092X/87 $3.00 + .00


# THE EFFECT OF BOTTOM REFLECTIVITY ON THE PERFORMANCE OF A SOLAR POND

J. Srinivasan and Abhijit Guha
Department of Mechanical Engineering, Indian Institute of Science, Bangalore, India 560 012

**Abstract**—The reflectivity of the bottom of a solar pond increases on account of the accumulation of dirt or the presence of undissolved salt. The effect of the reflection of the solar radiation at the bottom of the pond on the seasonal performance of the pond has been studied using a three zone model. The spectral reflectivity of dirt and common salt were measured in the laboratory and used in the analysis. The results obtained from the analysis show that the presence of dirt at the bottom of the pond does not affect the performance of the pond substantially. On the other hand, the presence of undissolved salt at the bottom of the pond results in substantial deterioration of the pond performance.

## INTRODUCTION

The solar pond has the potential to become the most economical method for the collection of solar energy in large scale. The use of the solar pond for generation of electric power has been demonstrated recently[1]. Solar ponds have also been used for process heating and chemical recovery[2]. Since a solar pond is exposed to the elements its performance can deteriorate with time. The two major factors reduce the amount of solar radiation absorbed at the bottom of the pond. The transmissivity of the pond can decrease dramatically on account of algae growth. This problem has been successfully solved by the use of copper sulphate or chlorine[3]. The absorption of solar radiation at the bottom of the pond can be reduced by the accumulation of dirt or presence of undissolved salt. There is no simple method for the removal of the dirt from the bottom of the pond. Hence it is essential to predict how the performance of the solar pond is affected by the reduction of solar absorptivity at the bottom of the pond. Kooi[4] was the first to study the effect of diffuse reflection at the bottom of the pond. His analysis indicated that the efficiency of a solar pond decreases linearly with the reflectivity of the bottom of the pond. His analysis did not, however, account for multiple reflections.

Hawaldar and Brinkworth[5] have considered the effect of bottom reflectivity on the thermal efficiency of a solar pond. They assumed, however, that the reflection at the bottom is specular. This assumption is not realistic since the dirt or undissolved salt at the bottom of the pond has rough texture. Hence the reflection will be diffused rather than specular. Katti and Bansal[6] considered multiple reflections but Guha[7] has shown that their analysis contains many conceptual errors. Hull[8] has considered multiple reflections between the bottom surface of the pond and the water-air interface at the top. Hull was able to express the modified absorptivity product defined by Kooi[4] in terms of four universal functions. Guha[7] has, however, found that the numerical values of these functions given by Hull were not correct. (Hull[14] has recently provided, the correct values of these functions.) The variation of absorptivity-transmissivity product with reflectivity is shown in Fig. 1. We see that results obtained by Guha[7] using Hull's method are higher than those presented by Hull[8]. Cengel and Osizick[9] have also considered the effect of multiple reflections in the solar pond. Their basic formulation seems to be different from that of Hull[8]. But the two approaches can be shown to be equivalent. Cengel and Osizick[9] have also accounted for the presence of diffuse solar radiation. They have shown that the diffuse solar radiation can be considered to be equal to direct solar radiation with a zenith angle of 60 degrees. Both Kooi[4] and Hull[8] concluded that the thermal efficiency of the solar pond decreases linearly as the reflectivity of the bottom of the pond increases. Cengel and Osizick[9] have, however, concluded that the energy absorbed in the storage zone of the pond increases as the reflectivity of the pond increases. They have therefore suggested the use of a partially reflecting bottom surface to increase the thermal efficiency of the pond. They came to this erroneous conclusion because they assumed that any solar energy absorbed at the bottom of the pond would be lost by conduction to the ground. Most of the work done so far has been limited to the study of the steady-state performance of the pond. In practical applications, it is desirable to know the effect of increase in bottom reflectivity on the seasonal performance of the solar pond.

## PRESENT MODEL

To study the effect of bottom reflectivity on the seasonal performance of a solar pond, we consider a simple three layer model of the solar pond. The temperatures of the bottom and top convective zones are assumed to be uniform but allowed to vary with time. The temperature profile in the gradient zone is assumed to be a quadratic. We did not

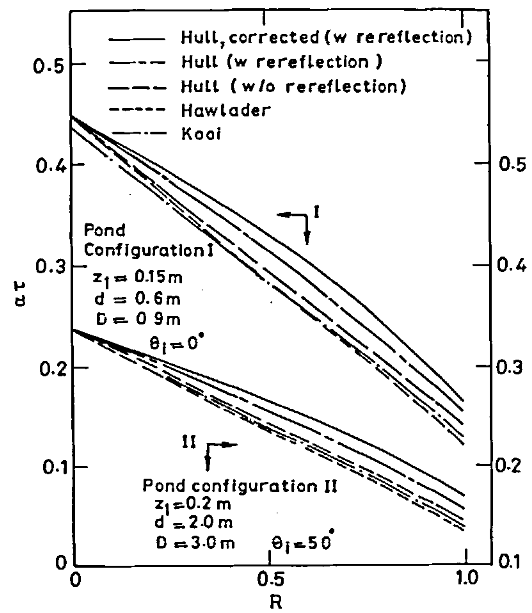


Fig. 1. Comparison of absorptivity transmissivity product $\alpha\tau$ as a function of reflectivity $R$ for different calculational methods.

assume the temperature profile in the gradient zone to be linear because this would result in the overestimate of heat loss from the lower convective zone. We can write three equations representing the energy balance in the three zones (see Fig. 2):

$$\rho C_p Z_1 \frac{dT_s}{dt} = K \frac{\partial T}{\partial Z}\bigg|_{Z_1} - Q_L + S[H_T(0) - H_T(Z_1)], \quad (1)$$

$$\rho C_p (D - Z_2) \frac{dT_b}{dt} = -K \frac{\partial T}{\partial Z}\bigg|_{Z_2} - Q_R - Q_G + SH_T(Z_2), \quad (2)$$

$$\rho C_p \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial Z^2} - S \frac{\partial H_T}{\partial Z}, \quad Z_1 < Z < Z_2, \quad (3)$$

where $\rho$ = density, $C_p$ = specific heat, $K$ = thermal conductivity, $T_s$ = surface temperature, and $T_b$ = bottom temperature.

The first two equations represent the energy balance on the upper and lower convective zone, respectively. $Q_L$ is the heat loss from the top surface by evaporation, convection and radiation. $Q_R$ is the rate of heat removal from the lower convection zone and $Q_G$ is the rate of heat loss to the ground. $S$ is the solar insolation and $H_T(Z)$ is the fraction of solar radiation which reaches level $Z$ directly or after multiple reflections. The third equation represents the energy balance in the gradient zone. This equation can be converted to an ordinary differential equation by assuming a quadratic temperature profile:

$$T = T_s + (T_b - T_s)\frac{(Z - Z_1)}{(Z_2 - Z_1)} + T_c \frac{(Z - Z_1)(Z - Z_2)}{(Z_2 - Z_1)(Z_2 - Z_1)}, \quad (4)$$

where $T_c$ (which is a function of time only) represents the deviation from linear profile in the gradient zone. Using the quadratic profile in eqns (1), (2), (3) and integrating eqn (3) from $Z_1$ to $Z_2$ we get

$$\frac{dT_s}{dt} = \alpha \frac{[T_b - T_s - T_c]}{Z_1(Z_2 - Z_1)} - \frac{Q_L}{\rho C_p Z_1} + \frac{S}{\rho C_p Z_1}[H_T(0) - H_T(Z_1)], \quad (5)$$

$$\frac{dT_b}{dt} = -\alpha \frac{[T_b - T_s + T_c]}{(D - Z_2)(Z_2 - Z_1)} - \frac{Q_G}{\rho C_p (D - Z_2)} - \frac{Q_R}{\rho C_p (D - Z_2)} + \frac{SH_T(Z_2)}{\rho C_p (D - Z_2)}, \quad (6)$$

$$\frac{dT_b}{dt} + \frac{dT_s}{dt} - \frac{1}{3}\frac{dT_c}{dt} = \frac{4\alpha T_c}{(Z_2 - Z_1)^2} + \frac{2S[H_T(Z_1) - H_T(Z_2)]}{\rho C_p (Z_2 - Z_1)}, \quad (7)$$

where $\alpha = K/\rho C_p$ = thermal diffusivity.

We now have three coupled ordinary differential equations. These can be integrated in time if we provide the daily solar radiation, ambient temperature, relative humidity and wind data. In the above equations the heat loss from the surface of the pond ($Q_L$) was calculated in a manner suggested by Kishore and Joshi[10]. The ground heat loss was calculated according to the correlation provided by Hull *et al.*[11]. This correlation takes into account the perimeter heat losses in a small solar pond. The fraction of solar radiation reaching a given level in the pond ($H_T$) was calculated according to procedure outlined by Hull[8]. We have, however, corrected the errors in numerical calculation of $f(\beta)$ (defined by Hull[8]) and used a four band model for spectral variations. The use of a very sophisticated spectral band model is not necessary because the transmissivity of a solar pond varies a lot on account of suspended matter and algae. The reflectivity of dirt and salt was measured with a spectrophotometer (see the Appendix for details). The above ordinary differential equations were integrated numerically using a forward difference scheme with a time step of 8640 seconds.

## RESULTS

The methods outlined in the previous sections were used to predict the performance of a 240 m$^2$ solar pond at the Indian Institute of Science, Bangalore (latitude 13°). The daily solar radiation, tem-

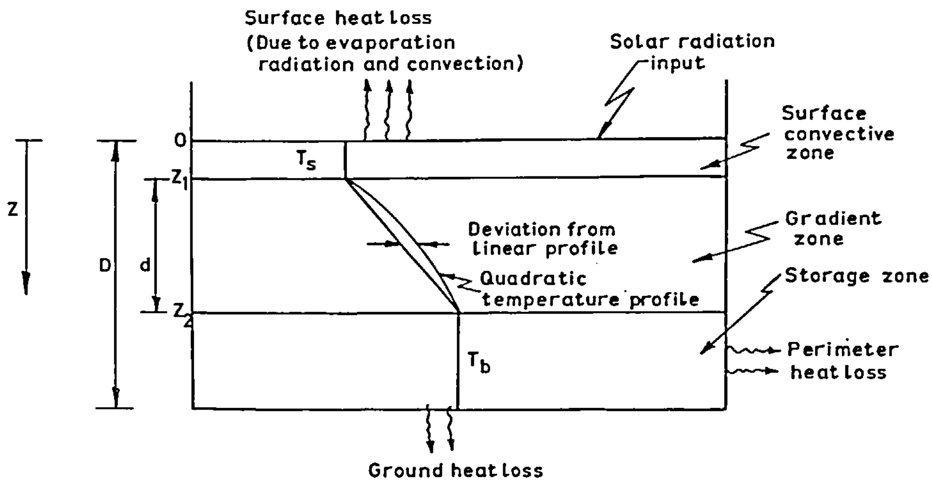


Fig. 2. Coordinate system.

perature, wind and humidity were interpolated from monthly data for Bangalore. These values are shown in Fig. 3. The equations were integrated for one year so that the initial transients are removed. The performance of the pond in second and subsequent years was found to be essentially same. The results presented in this paper are for the second (and subsequent) year's operation of a solar pond with the following characteristics:

| | |
|---|---|
| Pond location | Bangalore, India (latitude 13°) |
| Pond size and configuration | 240 $m^2$ (8 m × 30 m) |
| Zone thickness | |
| Storage | 1 m |
| Gradient | 1 m |
| Surface | 0.35 m |
| Ground thermal conductivity | 1.5 W/m K |
| Water table depth | 10 m |

We first examined the seasonal variation of storage zone temperature with no heat extraction. In Fig. 4 the variation of storage zone temperature for different bottom reflectivities is shown. We find the presence of dirt (reflectivity = 0.1) does not reduce the storage zone temperature substantially. On the

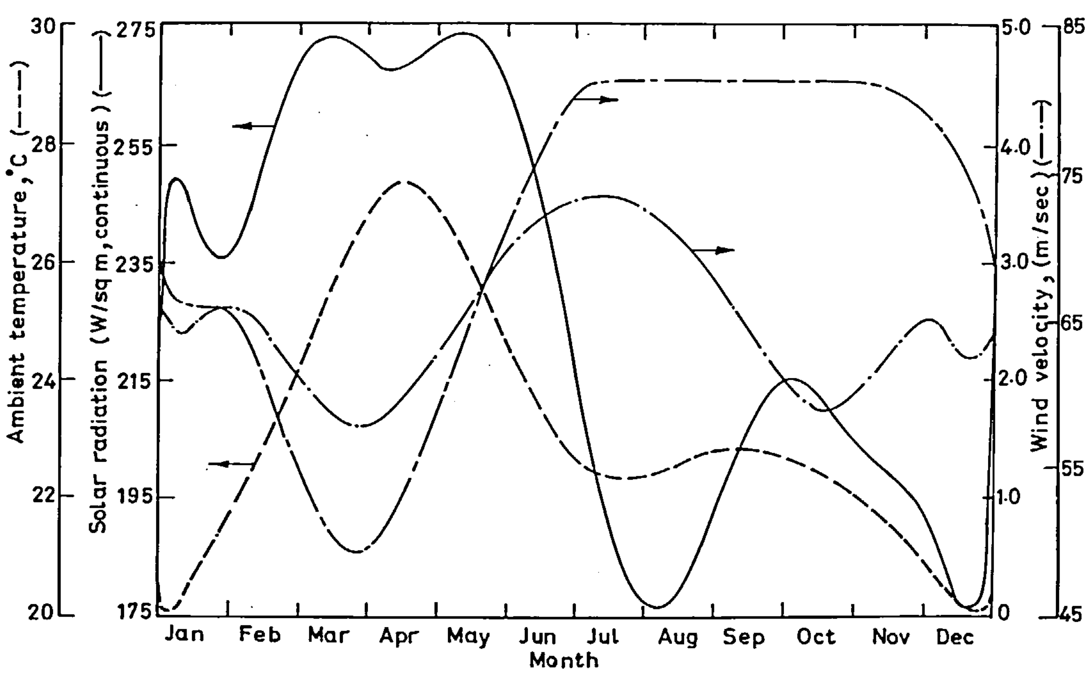


Fig. 3. Variation of solar radiation, ambient temperature, relative humidity and wind velocity *n* Bangalore.

other hand, the presence of undissolved or precipitated salt can reduce the storage zone temperatures substantially. The actual reduction will depend upon the grain size of salt which affects the reflectivity of the bottom of the pond. The use of undissolved salt piles has been suggested as a method for passive stabilization of gradient zone boundary by Hull[12]. This simple and ingenious technique may, however, result in substantial deterioration of solar pond performance. Hull[13] has indicated, however, that the salt pile need not cover the whole pond. Hence the reduction in efficiency indicated here may be an overestimate. In addition Hull has pointed out that dust can also accumulate on the salt pile and reduce its reflectivity. When the reflectivity of the bottom of the pond is high it is necessary to include multiple reflections between the bottom and water-air interface at the top. In Fig.

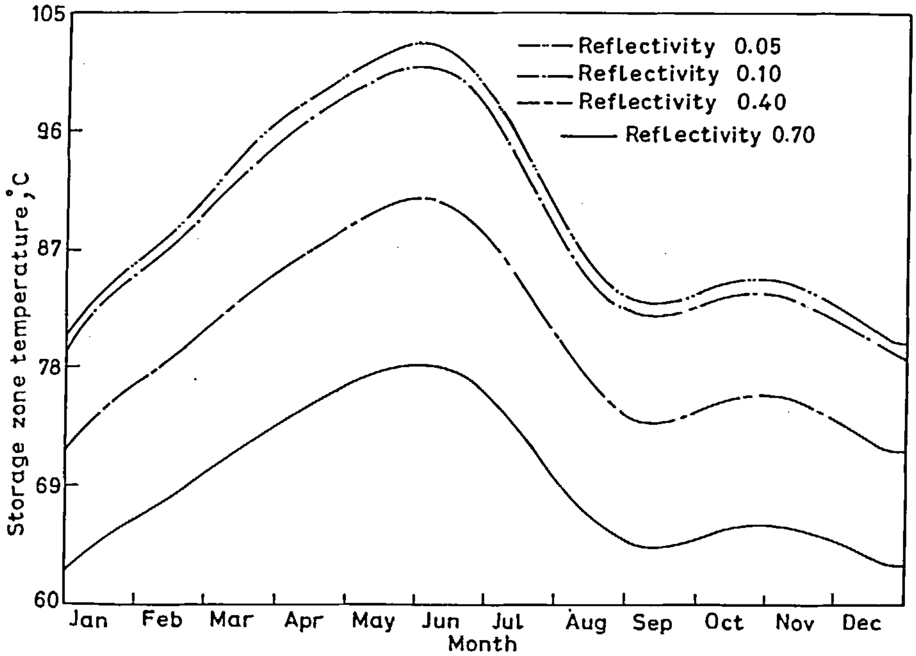


Fig. 4. Effect of bottom reflectivity on storage zone temperature.

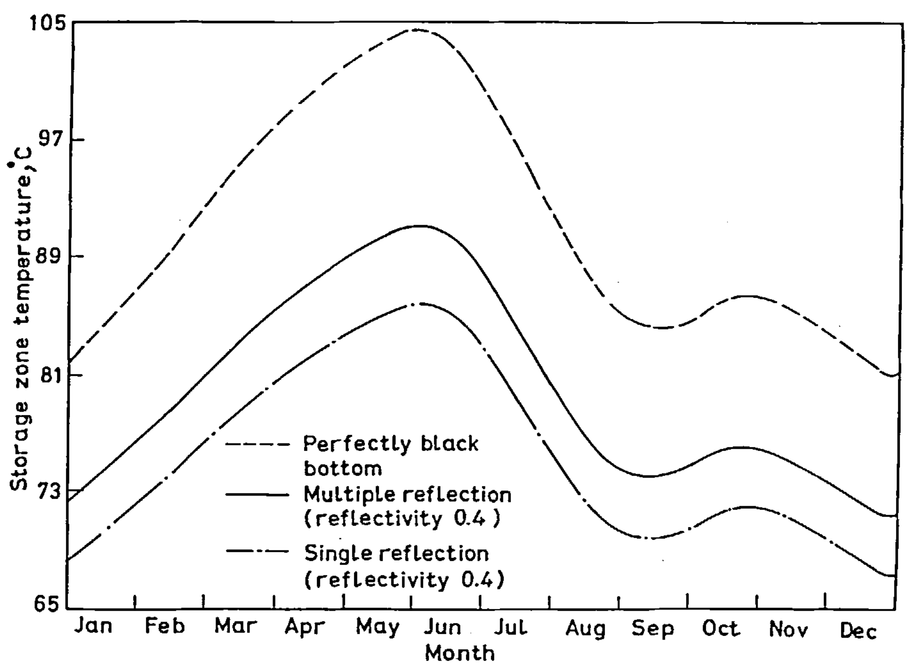


Fig. 5. The effect of multiple reflection on the storage zone temperature.

5, the storage zone temperatures in a pond with black-bottom is compared with one with reflectivity of 0.4. For the case of the pond with bottom reflectivity of 0.4 two results are shown. One includes only single reflection at the bottom of the pond while the other takes into account multiple reflections between the bottom surface of the pond and the air-water interface at the top. We find that the neglect of multiple reflections results in underprediction of the storage zone temperatures. Hence in solar ponds with high bottom reflectivities it is essential to include multiple reflections. In Fig. 6 the variation of yearly average heat extraction efficiency with reflectivity of the bottom is shown. We have considered three storage zone temperatures. It is assumed that heat extractions are undertaken

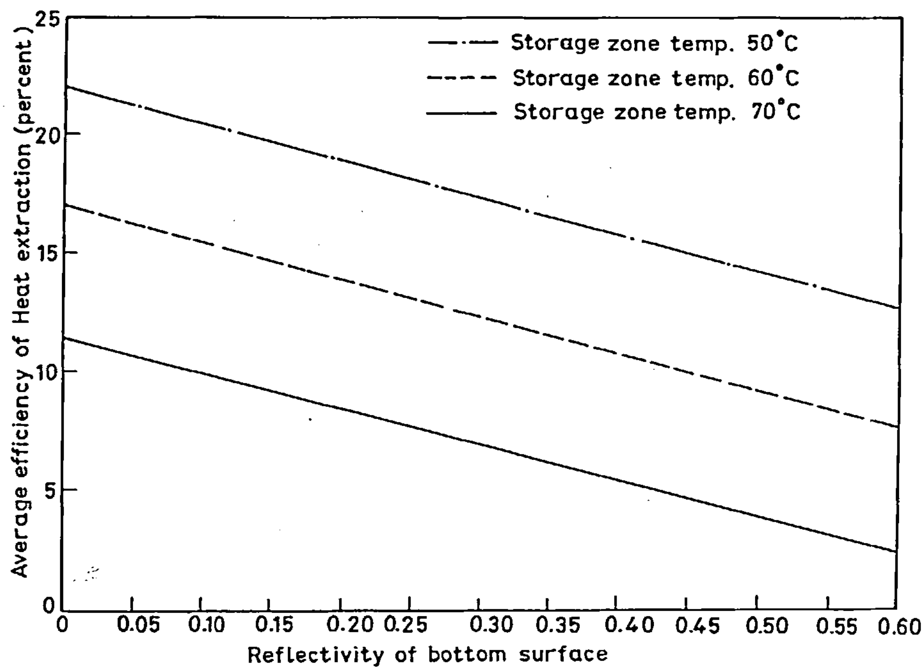


Fig. 6. Variation of yearly average efficiency of heat extraction with reflectivity of bottom surface (with storage zone temperature as a parameter).

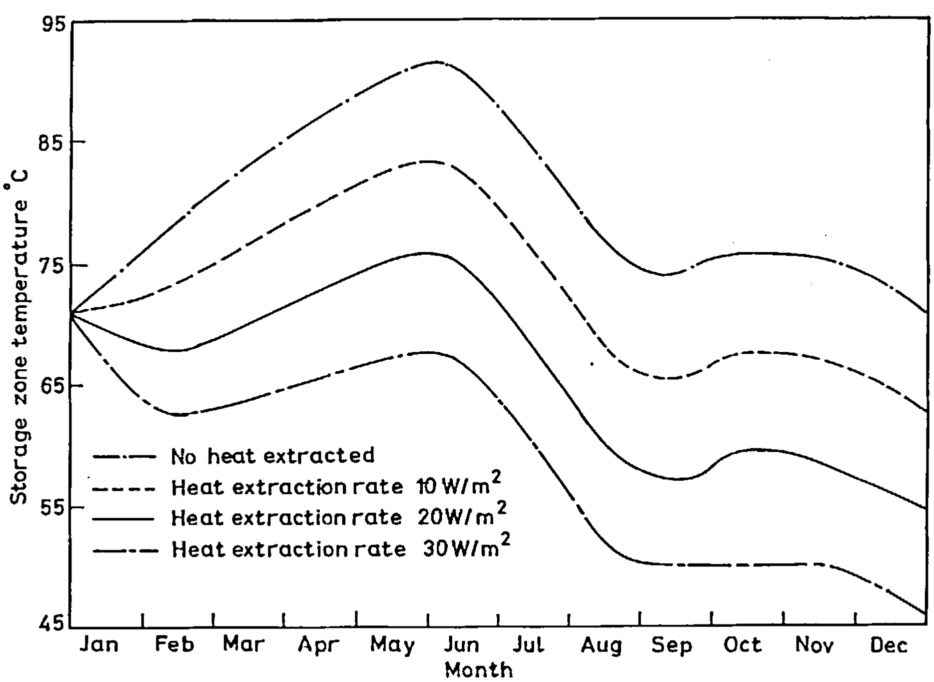


Fig. 7. Variation of storage zone temperature for different constant heat extraction rates.

so that the storage zone temperatures are maintained at the values shown in figure. We find that the yearly heat extraction efficiency decreases linearly with reflectivity of the bottom of the pond. This result is similar to that obtained by the steady-state analysis of Kooi[4] and Hull[8]. This implies that steady-state analysis is adequate for the evaluation of yearly heat extraction efficiency of solar ponds. In many process-heating applications the heat loads are seasonal. In such cases it is necessary to perform an unsteady-state analysis to obtain information on the performance of the pond in a given season. The effect of different heat extraction rates on the storage zone temperature (for bottom reflectivity of 0.4) is shown in Fig. 7. For example, if a certain process needs hot water at 70°C in winter then we cannot have heat extraction rates greater than 10 W/m$^2$.

## CONCLUSIONS

We have shown that the presence of dirt at the bottom of a solar pond does not affect its performance substantially. The presence of undissolved salt results in a large decrease in storage zone temperature or heat extraction efficiency. Hence the use of undissolved salt for passive stabilization of gradient zone must be looked at afresh since it results in a large reduction in storage zone temperatures or heat extraction efficiencies.

*Acknowledgements*—We thank the Karnataka State Council for Science and Technology for supporting this work.

## REFERENCES


1. H. Tabor, Review article on solar ponds. *Solar Energy* **27**, 181 (1981).
2. C. E. Neilsen, Status of solar pond technology and requirements for successful applications. *U.S.—India Binational Symposium*, Roorkee, August 1985.
3. C. E. Neilsen, Chapter on non-convective salt gradient solar ponds. *Solar Energy Handbook* (Edited by William C. Dickenson and Paul N. Cheremisinoff), p. 345. Marcel Dekker, Inc., New York and Basel, 1979.
4. C. F. Kooi, Salt gradient solar pond with reflective bottom. *Solar Energy* **26**, 113 (1981).
5. M. N. A. Hawaldar and B. J. Brinkworth, An analysis of the non-convective solar pond. *Solar Energy* **27**, 195 (1981).
6. Y. Katti and P. K. Bansal, Multiple reflection phenomenon in salt gradient solar ponds. *Solar Energy* **33**, 391 (1984).
7. A. Guha, Analysis of heat transfer in solar ponds. M.E. project dissertation, Mechanical Engineering Department, Indian Institute of Science, Bangalore, India 560 012 (1986).
8. J. R. Hull, Calculations of solar pond efficiency with a diffusely reflecting bottom. *Solar Energy* **29**, 385 (1982).
9. Y. A. Cengel and M. N. Osizick, Solar radiation absorption in solar ponds. *Solar Energy* **33**, 581 (1984).
10. V. V. N. Kishore and V. Joshi, A practical collector efficiency equation for non-convective solar ponds. *Solar Energy* **33**, 391 (1984).
11. J. R. Hull, K. V. Liu, W. T. Sha, J. Kamal and C. E. Neilsen, Dependence of ground heat loss upon solar pond size and perimeter insulation: Calculations and experimental results. *Solar Energy* **33**, 25 (1984).
12. J. R. Hull, Passive stabilization of gradient zone boundaries in solar ponds. *Proc. American Solar Energy Congress*, Anaheim (1984).
13. J. R. Hull, personal communication (1986).
14. J. R. Hull, Erratum. *Solar Energy* **36**, 575 (1986).


## APPENDIX: REFLECTIVITY MEASUREMENT

The reflectivity at the bottom of the pond can increase on account of dirt or the presence of undissolved salt. As far we know no published data are available on the spectral reflectivity of dirt or salt. We obtained a representative sample of dirt which had been deposited at the bottom of a 240 m$^2$ solar pond at the Indian Institute of Science, Bangalore. This dirt contained mostly sand. The spectral reflectivity of this dirt (in the wet condition) was measured using a UV-visible spectrophotometer (with an attachment for measuring diffuse reflectance). We measured also the spectral reflectivity of common salt used in the pond. We measured spectral reflectivity of three kinds of common salt. The commercial coarse (grain size 2 mm), commercial fine (grain size around 0.5 mm) and table salt (grain size around 0.2 mm). The spectral reflectivity of all these (and the black polyethylene linear) are shown in Fig. 8. From this figure we find that the spectral reflectivity increases strongly with wavelength. We find to our surprise that the spectral reflectivity of dirt is not very high. On the other hand, we find that the spectral reflectivity of common salt can be quite high. The spectral reflectivity of table salt is higher than 0.6. If salt precipitates out during the cooling of the storage zone its grain size can be as low as that of table salt. We can integrate this spectral reflectivity over the solar spectrum to obtain the total reflectivity. We need, however, information on the nature of the solar radiation spectrum at the bottom of the pond. This is shown in Fig. 9. This figure was obtained based on the spectral model proposed by Cengel and Osizick[9]. The nature of the solar

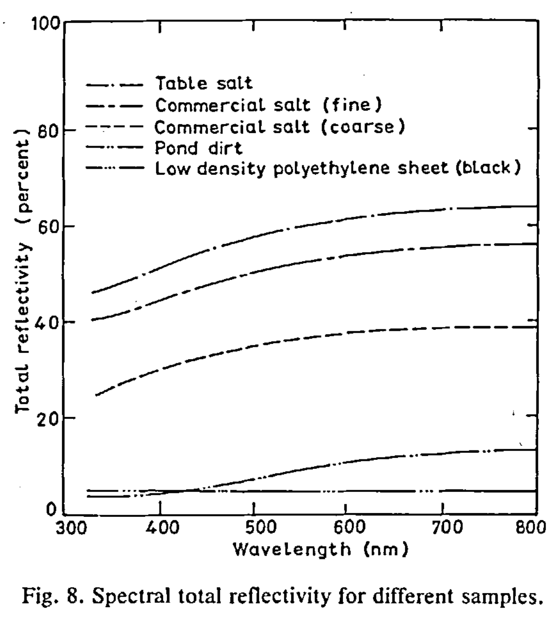


Fig. 8. Spectral total reflectivity for different samples.

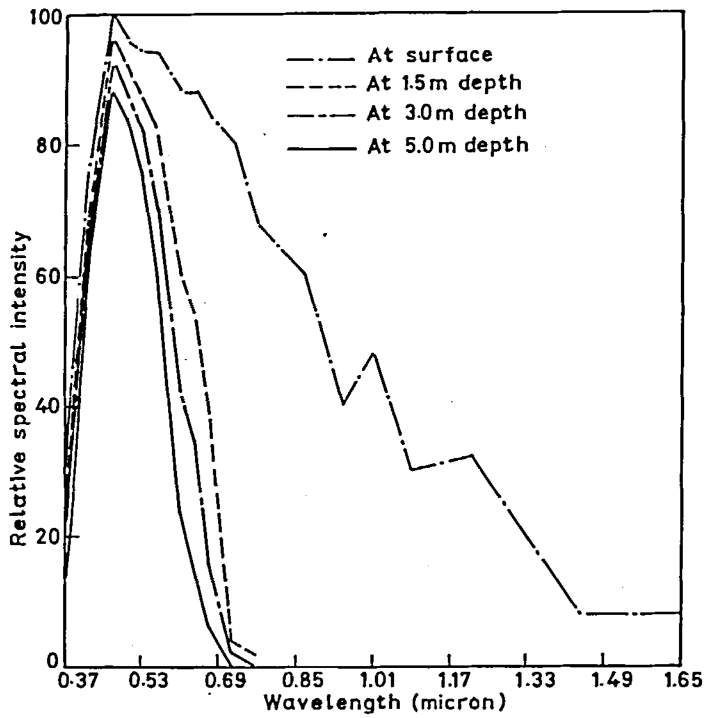


Fig. 9. Solar spectrum at different depths within a solar pond.

Table 1.

| | Total diffuse reflectivity, R | | | | |
|---|---|---|---|---|---|
| Pond depth | Black Polyethylene sheet | Pond dirt | Commercial salt (Coarse) | Commercial Salt (Fine) | Table Salt |
| 1.5 m | 0.05 | 0.084 | 0.351 | 0.498 | 0.585 |
| 3 m | 0.05 | 0.081 | 0.349 | 0.495 | 0.582 |
| 5 m | 0.05 | 0.078 | 0.492 | 0.579 | 0.579 |

spectrum depends upon the depth of the solar pond. The total diffuse reflectivity of the different materials for different pond depths is shown in Table 1. We find that the total reflectivity is not a strong function of pond depth. For the purpose of analysis we will assume the following representative values of the total reflectivity of the above materials: (1) black polyethylene, 0.05. (2) Pond dirt, 0.1. (3) Salt (commercial), 0.4. (4) Table salt, 0.6.